# ARM


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In 2001, JASON was charged by the U.S. Department of Energy, Office of Health and Environmental Sciences, to review the DOE Atmospheric Radiation Measurement (ARM) program. The JASON study focused on selected technical accomplishments of the ARM program and provided suggestions for future directions for ARM. The study also branched out to include an assessment of the role of ARM within the context of the larger climate change program in the DOE and within the context of the national effort under the auspices of the US Global Change Research Program (USGCRP).

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# Contents

# EXECUTIVE SUMMARY

The mission of the Department of Energy's Atmospheric Radiation Measurement (ARM) program is to utilize a suite of instrumental methods at selected fixed positions on the earth to collect a well-defined time series of atmospheric radiative transport data. Such data are needed to reduce the uncertainties in determining the factors that control the atmospheric relative humidity and cloud properties, which together account for a large portion of the variability in predictions of climate models to changes in atmospheric radiative properties including changes in greenhouse gases such as carbon dioxide. The ARM program is a $40 million/year effort within the context of the larger $1.7 billion/year U.S. Global Change Research Program.

In the summer of 2001 JASON reviewed the ARM program's progress to date and its proposals for future directions as presented by members of the ARM science team. The sustained operation of the suite of ARM instruments at the various ARM sites is a major accomplishment that serves well the U.S. capabilities for understanding important radiative transfer processes in the atmosphere. Significant progress has been made in a number of important scientific areas, including radiative transport properties in clear skies and of skies in the presence of certain types of clouds, improvement and validation of parameterizations that are used in certain types of general circulation models of the earth's climate, and development of observational tests of various modeling efforts on space/time scales that range from weather forecasts of hours/days to climatic time scales that are relevant to global change on the decadal to centurial time scale. ARM is also serving a valuable role by providing primary ground validation sites for several NASA satellite missions and by providing many well-calibrated time series of important atmospheric data on a climatologically significant time scale.

The ARM observational efforts are the core of the ARM program and should remain its highest priority. ARM could however greatly benefit from a more substantive collaboration and interaction with the modeling community, especially to define better the needed instrumental accuracy, instrument deployment capabilities, and siting options that arise in making choices regarding the various observational measurements that are central to the ARM program. Interactions with modelers could productively involve issues in weather forecasting and cloud system modeling as well as those related more directly to climate modeling. The assimilation of ARM data into better numerical weather and better climate models will also be enhanced by such a close coupling to modeling efforts. The "modeling partner" for ARM need not be either within the Department of Energy nor within the U.S., preferable as those options might appear.

The future evolution of ARM will depend, in large part, on what the primary focus of ARM is defined to be for the next decade. Climate monitoring would optimally involve deployment of a very different suite of instruments, many widely deployed sites, and different operational tactics than are required to perform parameterization validation for climate modeling.

Especially for climate monitoring sites should be located optimally and funded cooperatively and internationally, with the International Monitoring System that is now in place for verification of the Nuclear Test Ban Treaty as an example.

Overall ARM is a valuable component of the U.S. Global Change Research Program, and its work should be fostered and enhanced in the future. Our conclusions and recommendations, described at the end of this report, provide some sense of how to accomplish this.

# 1 INTRODUCTION

In 2001, JASON was charged by the U.S. Department of Energy, Office of Health and Environmental Sciences, to review the DOE Atmospheric Radiation Measurement (ARM) program. The JASON study focused on selected technical accomplishments of the ARM program and provided suggestions for future directions for ARM. The study also branched out to include an assessment of the role of ARM within the context of the larger climate change program in the DOE and within the context of the national effort under the auspices of the US Global Change Research Program (USGCRP).

ARM is a $40 million/year program within the DOE's Office of Health and Environmental Sciences. ARM was initiated in 1992 to focus on the radiative transport properties of the atmosphere. The impetus for this effort was an assessment by Cess et al., as well as others in the early 1990s, which concluded that "the single largest cause of variability in climate models is the treatment of clouds and their coupling to the earth radiation budget". Similarly, in 2001, a report issued by the U.S. National Academy of Sciences, "Climate Change Science: An Analysis of Some Key Questions", concluded that "much of the difference in predictions of global warming by various climate models is attributable to the fact that each model represents these [feedback] processes in its own particular way. These uncertainties will remain until a more fundamental understanding of the processes that control atmospheric relative humidity and clouds is achieved." Hence the ARM program efforts to determine better the underlying physics of radiative transport and the relationships between clouds, relative humidity, and the radiation distribution in the various parts of the ocean/atmospheric climate system is timely and of widespread interest.

The ARM mission can be summarized as follows:

- To collect well-defined time series of atmospheric radiative transport data by utilizing a suite of instrumental methods at selected fixed positions on the earth.
- To make observations on the scale of a General Circulation Model (GCM) grid box, and to understand the physics underlying the observations quantitatively enough to support the important parameterizations in the GCMs used in climate change studies.

In connection with this last task, it was anticipated that ARM data would feed in a natural fashion into the models built to understand climate change. A parallel computing effort (then called CHAMMP, now called CCMP) was established in DOE at the same time as ARM to foster this transfer of ARM observations to models.

The $40 million/year ARM budget is broken down approximately as follows:

- Engineering and operations, Intensive Operational Period (IOP) activity, and data archiving $\Rightarrow$ $27M
- Chief scientist, site scientists, science team programmatic costs $\Rightarrow$ $3M
- Science team proposals $\Rightarrow$ $10M

The DOE also has a computationally based effort in climate change modeling and model assessment, the CCMP program, which like ARM is an approximately $40 million/year program. For perspective, a breakdown of the total

global change funding at the various agencies in the U.S. in the year 2000 is approximately:

| | | |
|---|---|---|
| NASA | | $1149 |
| Satellites | $897 | |
| Science | $252 | |
| USDA | | $85 |
| NOAA (incl. GFDL) | | $95 |
| DOE | | $123 |
| NIH/USGS/EPA/SI | | $103 |
| NSF (incl. NCAR) | | $187 |

While ARM is clearly not financially a big player in the overall U.S. Global Change Research effort, it represents an important aspect of this program in its essential role of collecting accurate, long time series data on atmospheric radiation properties.

The ARM program runs three centralized facilities. The main site is the Southern Great Plans (SGP) site, located in Oklahoma, near Lamont. This site contains the most equipment resources and also benefits from being in the vicinity of auxiliary equipment such as Doppler radars and wind profilers run by the National Oceanic and Atmospheric Agency (NOAA) for use primarily by the National Weather Service. This site also has radiometers and other measurement capabilities deployed at various locations near the main site. Such locations are indicated on the map depicted in Figure 1.

Additional, remote, ARM sites are located in the Tropical Western Pacific (TWP) and on the North Slope of Alaska (NSA). The SGP site has been operational since 1994, the TWP site since 1996, and the NSA site became operational in 1998. ARM has additionally entered into an agreement with the Australian Bureau of Meteorology to operate a site in Darwin, in northern Australia.

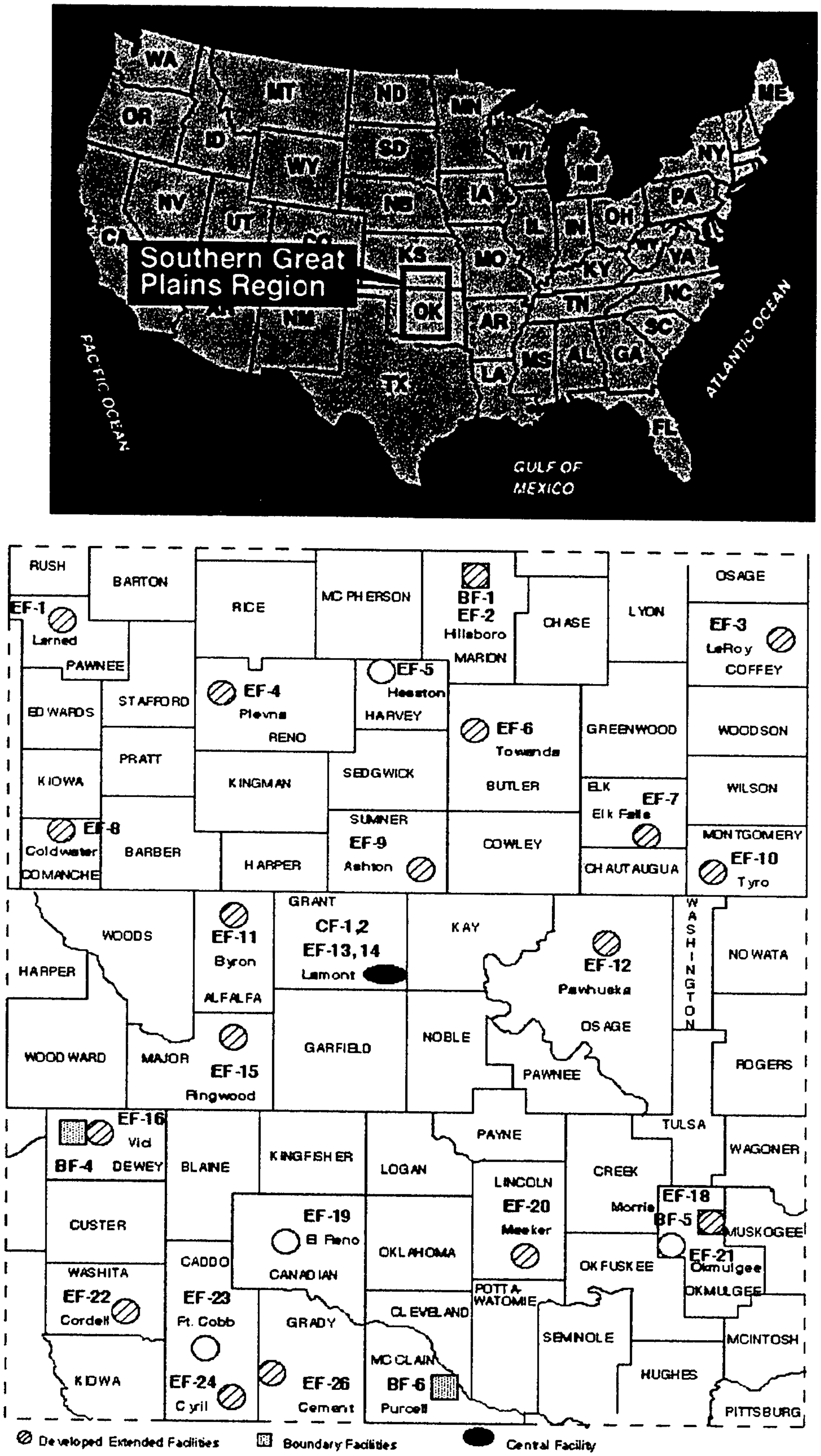


Figure 1: SGP site.

All three sites have a common core set of instruments currently deployed and operational. This core set includes:

- 35 GHz Radar (to measure cloud properties)
- Lidar (a pulsed laser to measure particle and thin cloud properties )
- Sky imagers (to measure cloud cover).
- Broad-band and narrow-band radiometers (to measure solar and infrared radiation)
- Microwave radiometer (to measure water vapor and liquid water)
- Meteorology sensors (to measure temperature humidity, winds)

Several of these instruments were developed through the ARM program and others were substantially improved by ARM–funded efforts.

## The charge to JASON

The study charge to JASON was as follows.

- Is ARM doing what it set out to do?
- What are the appropriate future directions for ARM?
- Evaluate the balance between operations and science.
- Provide comments on ARM efforts to measure radiative absorption properties in clear skies and by clouds
- Evaluate the value added of more sites relative to more fully instrumenting fewer sites

JASON also specifically requested the ARM briefing team to address the following questions.

- What scientifc questions has ARM answered in the past 5 years?
- What scientific questions does ARM expect to address in the next 5 years?
- What additional questions would be addressed in the next 5 years if ARM's budget were doubled?
- What important scientific results have come out of data from the remote sites that could not have been obtained using data from the SGP site?
- Are the ARM data readily accessible to the climate modeling and weather communities?
- Are the ARM data being used by those communities?

Briefings were provided by the ARM team, including Tom Ackerman, ARM Chief Scientist, PNNL; Dave Randall, Colorado State University (cloud system models); Minghua Zhang, SUNY Stony Brook (closing boundary flux problems); Christian Jakob, European Center for Medium Range Weather Forecasting (ECMWF) (use of ARM data in weather forecasting and cloud modeling); Tony Del Genio, NASA Goddard Institute for Space Sciences (use of ARM data in GCM's); Joe Michalsky, SUNY Albany (anomalous absorption); Warren Wiscombe, NASA Goddard Space Flight Center (ARM instrumentation); Bob Ellingson, University of Maryland/Florida State University (anomalous absorption); Bill O'Hirok, UC Santa Barbara (4-D cloud models); and Jay Mace, University of Utah (Cloud models). In addition, JASON received requested briefings from Dave Bader of DOE regarding the

DOE's climate modeling efforts, from Ed Sarachik of the University of Washington regarding the recent reports on climate modeling efforts in the U.S. issued by the National Academy of Sciences, and from Isaac Held of NOAA's Geophysical Fluid Dynamics Laboratory (Princeton, NJ) (a leading climate modeling center in the U.S.), for a perspective of the ARM program from a climate modeling viewpoint.

This report contains three major sections. In the first (Section 2), we discuss aspects of three different types of ARM observational programs, distinguished by their goals, instrumental capabilities, and matching of observations to certain science questions. In Section 3, we discuss interactions between the ARM program and three different types of modeling efforts: climate modeling, weather modeling, and cloud system modeling. We then present in Section 4 additional findings with respect to the study charge questions on (1) ARM data access, (2) interactions between ARM and other climate change efforts, (3) production of value added data products by ARM, and (4) options for additional sites. Finally we detail our findings and conclusions in response to the study charge and present recommendations for future evolution of the ARM program.

# 2 ARM OBSERVATIONAL PROGRAMS

## 2.1 Radiative Transfer in a Single Column

### 2.1.1 Clear Sky Measurements/ ARESE I and ARESE II

One of the major purposes of ARM is the establishment of the radiation budgets at different levels in the atmosphere as a function of cloud extent. The data sets obtained in the ARESE I and II experiments comprise a significant component of this effort. In the ARESE (Atmospheric Radiation Enhanced Shortwave Experiment) experiments, aircraft above the clouds carried upward-looking and downward-looking radiometers that measured the downwelling and upwelling radiation, respectively, at the position of the aircraft. These data were then compared to radiometric measurements below the cloud, obtained either from a second airplane (in ARESE I) or from a fixed ground site (in ARESE II).

These experiments were carried out at the Southern Great Plains site in Oklahoma, at a latitude of 37° N. Both ARESE I, in October 1995 and ARESE II, in March 2000, occurred near the time of a solstice. At 37° N at noon, the solar flux at the top of the atmosphere (TOA) was 1086 $W/m^2$. The average over the twelve-hour day was 691 $W/m^2$, and the average over the 24-hr day was 346 $W/m^2$. (The measurements are given for the time of day of the airplane flights; they are not adjusted to noon values or to an average. Therefore comparison could potentially be made to TOA values at the correct time of day. However, this is not needed because the upper altitude measurements are known from the ARESE data). "Absorptance" is

defined as

$$\text{"absorptance"} = [\text{DWR(upper) - DWR(lower)}]/\text{DWR(upper)}$$

and the "absorption" is defined as

$$\text{"absorption"} = [\text{DWR (upper) - DWR(lower)}],$$

where in both cases DWR is the downwelling shortwave (wavelengths less than a few microns) solar radiation at the position of interest.

It is important to note at the outset that the upper aircraft altitudes in the two experiments were 13.5 km and 7 km, respectively. In ARESE I, the lower altitude information was obtained by another aircraft at 500 m. Both aircraft were synchronized in vertical positions for a large portion of the experiment, and the radiometric data of ARESE I were therefore analyzed for essentially the entire flight duration. In ARESE II the upper-altitude aircraft was flown directly over the extensive permanent ground array of radiometers at the ARM SGP site central facility (the so-called CART site), and data were analyzed only for the portion of the flight path in which the aircraft were close enough to the ground-based radiometers to allow the column absorptance to be determined reliably. The use of only one aircraft, however, greatly simplified the experimental protocol so that a much more extensive data set could be collected in ARESE II than in ARESE I. Significant spatio-temporal variability in the radiometric signals was observed in ARESE I because of the broken clouds present at the time of the experiment. In contrast, deliberate efforts were made in ARESE II to perform the experiments on days that had a more horizontally uniform cloud coverage over the CART site, as predicted by the National Weather Service and as verified by overflying airplane and satellite photography, as well as by the ARM SGP ground radar.

Concern was engendered by ARESE I because its measurements showed that clouds absorbed significantly more shortwave radiation ($\approx$ 10–20 W/m$^2$)

than was predicted by several radiative transfer models, including those used in the NCAR (National Center for Atmospheric Research) general circulation model denoted as CCM2 (community climate model #2). However, at least as significant was the finding that the radiometric flux measurements obtained by several groups during the ARESE I experiment disagreed with each other by on the order of 10 $W/m^2$ (i.e., on the order of the discrepancy being investigated). Additionally, a discrepancy of 10 $W/m^2$ or greater was also observed between models and instantaneous radiation measurements obtained in clear sky conditions. The magnitude of such discrepancies should be interpreted within the context of typical atmospheric $CO_2$ doubling scenarios that correspond to approximately 4 $W/m^2$ of increased radiative forcing. An additional complication for understanding the physics as of the date of ARESE I was that clear sky absorption data derived from simultaneous satellite and ground-based measurements at a non-ARM site, in Boulder, Colorado, seemed to be in better agreement with models than was observed in the ARESE I experiment at the SGP ARM site.

Great effort was expended by ARESE II to insure that the radiometers were very well calibrated, especially against each other. The result of this effort was that measurements by several radiometers and by several analysis groups agree to within 10 $W/m^2$. This is important progress.

Table 1 presents the values of absorption and absorptance in ARESE II for different days, as presented to JASON. The clear sky data are also summarized in Figure 2. This figure additionally presents the results of two different radiative transfer models for the clear sky conditions of concern on these same days.

A simple clear-sky model in which the atmospheric absorption is proportional to density has about 3% of the downwelling radiation (DWR) being absorbed above 13.5 km; another 3% being absorbed between 13.5 km and

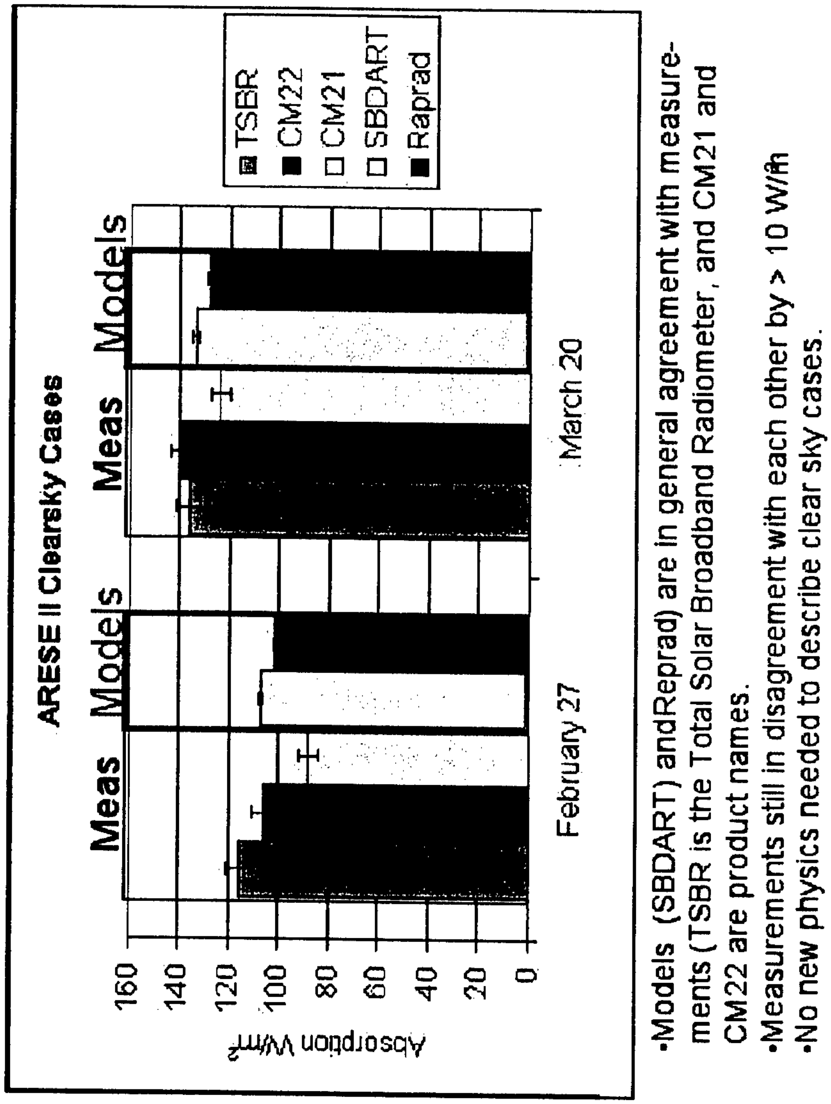


Figure 2: Measurements and modeling of atmospheric absorption in clear skies in the ARESE II experiment.

Table 1: Absorption in the measured altitude range

| Condition | Date | Meas. ($W/m^2$) | SBDART* ($W/m^2$) |
|---|---|---|---|
| Clear | 2/27 | 100 | 100 |
| Clear | 3/20 | 135 | 125 |
| Cloudy | 3/3 | 170 | 180 |
| Cloudy | 3/21 | 210 | 200 |
| Cloudy | 3/29 | 215 | 205 |

| Condition | Date | Meas. (%) | SBDART (%) |
|---|---|---|---|
| Clear | 2/27 | 12 | - |
| Clear | 3/20 | 11 | 11 |
| Cloudy | 3/3 | 18 | 18 |
| Cloudy | 3/21 | 21 | 18 |
| Cloudy | 3/29 | 22 | 18 |

* SBDART is the Santa Barbara DISTORT Atmospheric Radiative Transfer Model

7 km, and 10% being absorbed in the lowest 7 km. Up to 30% more will be absorbed in heavy overcast conditions.

The absorptance results for ARESE I for clear skies were about 15%, somewhat higher than in ARESE II. For cloudy skies, the presentation was somewhat different. Instead of simply defining "cloudy", the results were separated into "scattered", "broken", and "heavy overcast", with absorptances being 19%, 28%, and 36%. The analyzed cloudy days at ARESE II imply a narrow range of absorptances that were not in fact seen in ARESE I. This is probably because the clouds in ARESE I were significantly heavier and thicker.

The models to which we may compare the measurements of ARESE II are radiative transfer models, not GCMs. (GCM models are similar, but with grid spacings that are a factor of $10 - 10^2$ larger.) Radiative transfer models use Monte-Carlo ray tracing through realizations of clouds and find

the average absorption and transmission. They can be divided into three types:

1. Spectral line by spectral line, with cross-sections expressed as a function of incoming wavenumber, outgoing wavenumber, and scattering angle. Photons are followed by Monte Carlo through many generations of scattering and absorption until the output atmospheric depth is reached. (Examples of this type: O'Hirok and Gautier; JPL; Boston Smithsonian)

2. Treat the spectrum in bins of wavenumber. Rather than following each photon individually, convolve the input spectrum with the scattering after a given depth interval and thus form a transmitted spectrum. This is much faster than type (1), yet still provides high accuracy. (Examples of this type: RapRad, the Rapid Radiation Transfer Model, by Ackerman; Fu and Liou)

3. Treat some of the empirical spectral distributions as exponential functions of depth into the atmosphere, so that the final distribution is a sum of exponentials. (Examples of this type: SBDART, the Santa Barbara DISTORT Radiative Transfer Model).

In clear skies, all of the models also require a determination of the aerosol content of the atmospheric column of interest. For ARESE I and ARESE II, the aerosol content was determined from the ground instrumentation over the SGP site on the days of the experiments. Finally, the water vapor content of the column is needed input data, and measurements of column water vapor are also available for the days of interest. The models then compute the water vapor absorption, scattering and absorption by aerosols, and Rayleigh scattering in the column of interest, to predict the absorbance in the atmospheric column under the conditions of concern. In the presence of clouds,

the Monte Carlo ray tracing is used, along with a description of the cloud optical properties based on the cloud droplet size distribution, liquid water content, and ice content, to arrive at a column absorptance.

As seen in Figure 2, both the SBDART model and an ARM group model (Raprad) of Ackerman et al. agree with the clear sky ARESE II measurements, within the variation of the radiometric measurements among the several measurement groups on the days of concern. Hence there appears to be no new physics required to describe the absorption on clear sky days, at least for the three days for which such measurements are available from ARESE II. The clear sky discrepancy observed in the ARESE I experiment has apparently largely been explained by a recently discovered bias in the radiometer calibrations, which accounts for a systematic error on the order of 15-20 $W/m^2$, primarily in the diffuse portion of the radiation. This was not accounted for in analysis of the ARESE I data.

### 2.1.2 Aerosol Contributions

We have noted above that the clear-sky predictions and measurements as presented to the JASONs agree with each other to within reasonable error. However, this agreement is for radiative fluxes integrated over wavenumber, and is not better than about 1%, which corresponds to 10 $W/m^2$. There is a way to learn more by distinguishing between direct and diffuse radiation. The direct beam is reduced by both scattering and absorption. Scattering is the source of the diffuse radiation. We assume that the diffuse radiation is mainly a single-scattering phenomenon and thus need to consider three processes:

1. Molecular scattering.

2. Aerosol (that is, particulate) scattering.

3. Gaseous absorption

Molelcular scattering is quantitatively well-described and can be used as a standard reference. Aerosol contributions are important and considerably variable. For example, during ARESE I, nearby farmers were plowing their fields in preparation for planting. The resulting dust and grit in the atmosphere had a major effect on the opacity of a "clear-sky" atmosphere. On the other hand, ARESE II took place at a time of year when the atmosphere was much cleaner. Finally, gaseous absorption is known if the constituent species are known.

Measurements during ARESE II were able to determine the solar direct and diffuse downward spectral distribution arriving at the ground, and to compare it with models that contain contributions from known aerosols and gases. The result is good agreement for the direct beam, and a significant disagreement with diffuse radiation where specifically the diffuse beam was higher by an amount that is roughly flat in wavelength and has an integral of 10-15 $W/m^2$. The direct beam agreement assumes that scattering processes reduce the flux. Each scattering process that removes photons from the direct beam must put the same number of photons back into the diffuse radiation. However, the expected increase in diffuse radiation was not observed. Therefore part of the direct-beam reduction has to be moved from scattering to absorption, to reduce the diffuse radiation. This would apparently require a "mystery gas." However, more than just introducing an unexpected absorber, the observations also require removing much expected aerosol scattering. The amount of aerosol scattering was measured independently with a photometer so that measurement is now in disagreement with the amount of aerosol scattering that is necessary for the model. This remaining disagreement between models and experimental data still remains

to be resolved.

Further evidence that attention needs to be focused on reconciling differences between various models can be found from clear sky radiative transfer observations at the North Slope of Alaska (NSA) site. Data for downwelling and upwelling radiation at this site are summarized in Figure 3, as are the results of several different models. Even though these data were obtained under a clear sky condition, the magnitude of the discrepancy between the different models is striking. Of special note is that the least accurate model of the ones tested was the one used in the CCM2 NCAR GCM. Apparently the disagreement results primarily from how the models treat the surface ice albedo. Clearly, this discrepancy needs to be resolved, and ARM data can be useful to define and resolve underlying differences in the various radiation codes available to the community, and to assure that the parameterizations of such models used in the GCM's are in accord with the more detailed single column models and with ground truth measurements at the ARM sites.

### 2.1.3 ARESE II Data in Cloudy Sky Conditions

In the presence of clouds, there is still a disagreement as to whether there is more absorption than models predict. However, unlike ARESE I, the area of disagreement has moved from the measurements to the models. Figure 4 shows the data obtained by three different radiometer sets, which are in general agreement with each other (but, we note, only to the level of 20-30 $W/m^2$).

The SBDART model, when run by the group led by Ackerman, apparently is in good agreement with the ARESE II data on cloudy days (Figure 4), within the dispersion between the various radiometer measurements and when considering the variation in the data on the ARESE II flight path for

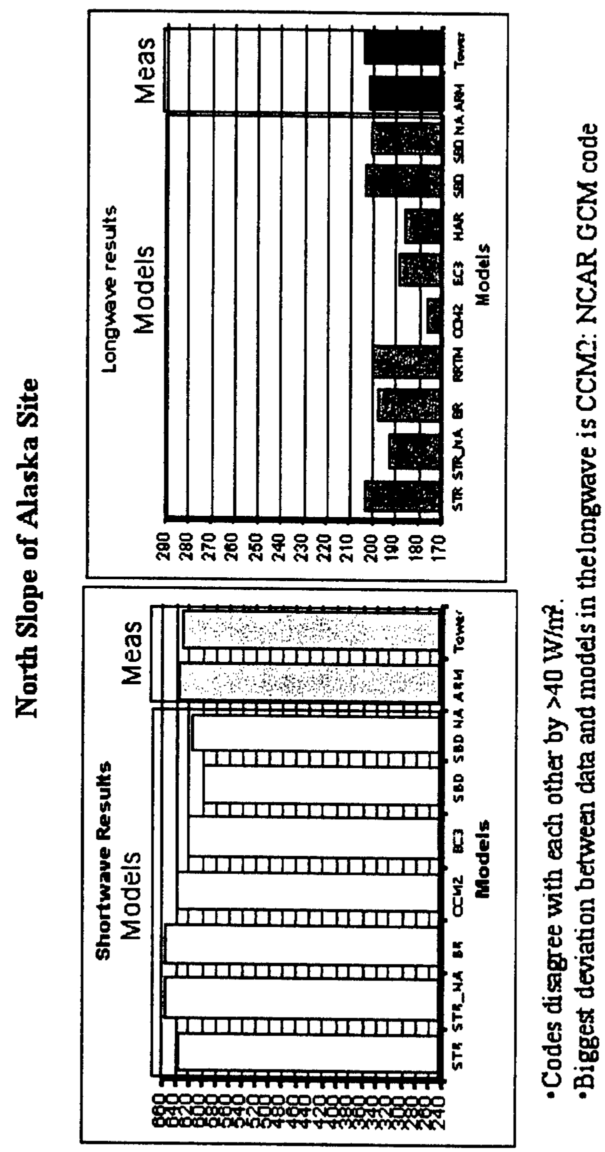


Figure 3: Differences in radiative transfer codes as compared to experimental measurements in the shortwave (left) and longwave (right) at the North Slope of Alaska ARM site in clear sky conditions.

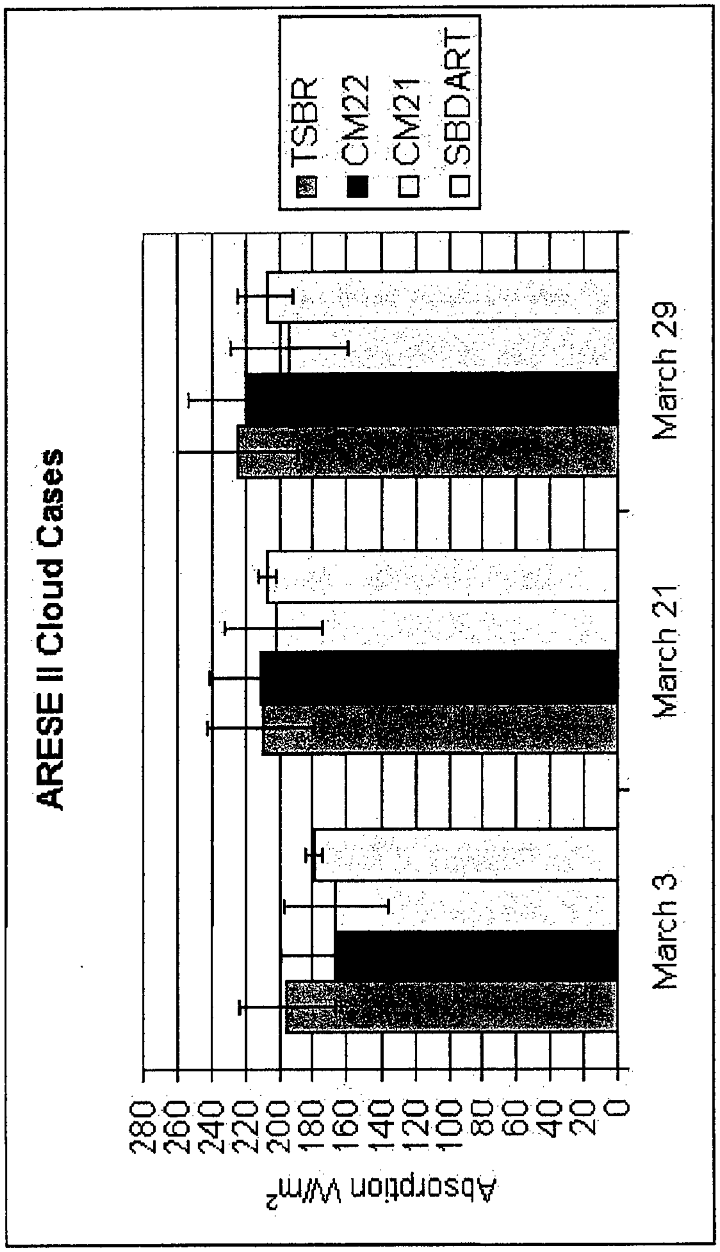


Figure 4: Comparison of measured and predicted column absorption under cloudy conditions in the ARESE II experiment.

the same radiometer types (shown as error bars in the figure). Similar agreement between models and measurements is apparently obtained when other models are used. Additionally, however, the results of one other group were mentioned to us: that of Pope and Valero. These workers are not running their own models but are running the models of many other groups, including the SBDART model being run by Ackerman et al. Pope and Valero claim that their model runs produce substantially less cloudy-sky absorptance (15%) than the model run by other groups and than the ARESE II measurements (18-22%). They additionally maintain that there is no reasonable set of input parameters to the model that are capable of producing the observed absorptance values, apparently in contradiction to the results of Ackerman and others who have produced higher absorptances using these same models for the same flight conditions. Thus different model results are emerging from different people running the same models. These are questions to be resolved by the participants, and we must abstain as to whether a discrepancy between models and measurement actually remains at the present time, and as to whether it is of a significant enough level to warrant further investigation by ARM.

### 2.1.4 Future Radiative Transfer Measurements

Moving forward, it seems clear that the single column clear sky and cloudy sky radiative transfer question is well matched to the space and time scale of the observational capabilities of the ARM sites. Consequently it seems appropriate to collect analogous data at the TWP and NSA sites in ARESE-like experiments to characterize the radiative transfer properties of the different cloud types that are present at those two sites. In addition, the data of ARESE I should be reanalyzed carefully, incorporating the identified biases of the radiometers into the re-analysis of those data; it would be es-

pecially interesting to determine whether the clear sky anomaly persists in re-analysis of those data. It is of additional interest to determine whether the models are capable of producing agreement with radiometric measurements in the broken cloud conditions (which of course are more frequent than complete, horizontally uniform, clouds over any particular GCM grid box-sized atmospheric column) that were observed in ARESE I.

We also note that valuable data ought to be available from the radiometers at the perimeter of the SGP ARM site, from the radiometers at the other ARM sites, and from the radiometric data at the SGP site during non-ARESE I and non-ARESE II periods. The GOES satellite data could yield the information on cloud fraction, and GOES is traceable to ERBE (and presumably now to CERES) through a retrieval algorithm that allows calculation of a TOA downwelling radiation flux from the satellite observations. Hence, when the satellite data are combined with the aerosol retrieval data from the ARM instrumentation it ought to be possible to predict, using a model, the flux at each radiometer in the ARM constellation, at any instant in time, for the length of the historical record that ARM has compiled to date. Do persistent biases exist between models and measurements under certain clear sky or cloud conditions? Are the mean values in agreement with the models but are there systematic differences under certain types of cloud structures, for certain types of clouds, at certain spatial scales, etc.? Much could be learned about the issue that is central to ARM: radiative transfer properties of the atmosphere, by combining the existing satellite data with the archival data by the ARM program to date. Otherwise, if this is not possible for some reason, one should ask what additional instrumentation needs to be deployed at the ARM sites to allow closure of this problem to occur through use of the collection of ARM radiometers and auxiliary instrumentation.

## 2.2 Use of ARM Data for Obtaining Improved Cloud Parameterizations

A second, separate class of technical issues that can be addressed profitably by the ARM program involves investigating and/or validating functional relations between external variables and cloud properties. In this mode, the ARM data obtained from a combination of instruments, dates, sites, and in a variety of column conditions are used to establish, invalidate, validate, or improve (as the case may be) various parameterizations that are either currently imbedded in GCM's or that are contemplated to be imbedded for producing improved GCMs. ARM sites can provide a fertile testing ground for evaluating such functional relationships, and this mode of use of ARM data provides perhaps the most compelling case at present for the value of collecting a time-series of data over a fixed spatial location.

A specific presentation to JASON focused on the work of Del Genio and co-workers at NASA/GISS (Goddard Institute for Space Studies) who have used ARM data to develop improved cloud parameterizations for use in the NASA/GISS GCM. The specific issue of interest is how GCM's deal with the radiative transfer of clouds within a GCM grid box. Clearly, the optical properties of a thick cloud that covers 50% of the horizontal plane of the grid box will be different than the optical properties of a thin cloud that fully covers that same grid box. Some GCM's keep cloud thickness fixed and adjust the cloud fraction based on the other variables in the grid box at the time of interest. However, in order to tune the average global albedo to the ERBE data, and to produce the observed cloud fraction coverage obtained from satellite data as well as to produce the correct average radiative flux budget at the surface of the earth, under cloudy conditions these models produce extremely unrealistic liquid water contents in an atmospheric column. Hence

there is a need for improved cloud parameterizations that do not suffer from these shortcomings.

Satellite data indicate that the albedo of low clouds decreases with warming over much of the world. Del Genio and co-workers analyzed data from the ARM sites and concluded that the ARM data suggest that such clouds are thinner. The ARM data were further used to suggest that the situation arises from the increasing frequency of convective planetary boundary layers over midlatitude continents. This produces a positive cloud feedback for these types of clouds.

In contrast, Del Genio and co-workers deduced from ARM data and from satellite data that deep convective clouds brighten as rain rate increases. This produces a negative cloud feedback for these types of clouds.

Both types of behavior were then captured through improved parameterizations that were incorporated into the NASA/GISS GCM. The results of using these parameterizations in a $CO_2$ doubling run were then compared to the baseline model of the NASA/GISS GCM and to the results of that model when run using four different cloud parameterizations. Del Genio and co-workers observed that the cloud parameterization that was consistent with the ARM data produced a global decrease in cloud cover upon warming (as observed in the latter 20th century from satellite measurements of the earth), yet middle and high-latitude continental cloudiness increased with warming (also as observed from satellite measurements in the latter 20th century). In addition, the overall cloud feedback was positive, as opposed to the neutral or perhaps negative cloud feedback that results when the optical properties of clouds are prescribed to have a fixed thickness and increasing liquid water content as the temperature increases. Del Genio and co-workers further suggest that the neutral cloud feedback that resulted from fixed cloud optical properties, which produced temperature increases upon a doubling of atmo-

spheric $CO_2$ at low end of the 1.5–4.5°C range commonly quoted in the IPCC reports, are likely not correct, and therefore that more warming is likely to occur than the lower limit established by these earlier GCM runs.

This approach is meritorious for several reasons. The combination of column data from ARM and satellite data enhanced the impact of both types of observations. The approach required, and made use of, simultaneous measurements from multiple instrument types that were available at the ARM site. The issue of interest is a problem that is well-matched to the space/time scale of ARM observations. And finally, the approach took advantage of a climatologically significant archival time series of the needed quantities that had been collected by the ARM instrumentation.

Clearly such relationships should also be extended to the TWP and NSA sites if possible, since the global validity of such relationships is important to their application in GCM's. Furthermore, the ARM program is in an excellent position to provide the needed observational tests of such relationships. The above example seems to be an exemplary use of the ARM data and observational capabilities, typical of those to be encouraged in future work within the ARM program.

## 2.3 Closing the Boundary Flux Problem in Support of Single Column Modeling

A more ambitious, but less clear, use for ARM data is in support of single column modeling. Simply put, if one specifies the large-scale atmospheric fields on the scale of a GCM grid box, can one predict the cloud field properties on that same spatial scale? In principle, ARM data might be able to help formulate which parameterizations perform well in the single column

model (SCM) description of such a grid box and therefore be useful in developing new inputs to GCM's from a SCM starting point.

This problem is apparently highly underdetermined given the present observational measurement configuration even at the SGP site, and is certainly underdetermined at the TWP and NSA sites. Improved estimation of certain quantities can be obtained through insuring conservation of mass and energy within the column of interest, by constraining estimated flows with additional flux measurements. A variational principle is then used to obtain improved estimates of the desired quantities within the error limits of the measurements comprising the boundary forcing data. For example, measurements of the net flux of water vapor at various heights at the boundaries of the column can be constrained to conserve water mass through introduction of the additional measurements of the net water flux entering the top of the column, leaving the bottom of the column, and the local change of the water in the column.

A good example of this approach can be found in the work by Zhang, some of which is summarized in Figure 5. The top two panels show the observations of temperature and water mixing ratio, respectively, as a function of time for a several month period over the SGP ARM site. The middle two panels show the errors produced by using the NCAR CCM2 model to compute these same two quantities, given the measurements only at the boundaries of the grid box obtained from the ARM site during the same time period. The lower two panels show the errors produced by use of the same model and same input data, but with constraints introduced by additional measurements obtained during the IOP that was used to address this boundary flux issue. Clearly, reduced errors were produced when the variational principle procedure, along with the constraint data, were used relative to when the raw ARM SGP data were used to force the same SCM.

**Observations of T, $H_2O$ mixing ratio**

**Difference between observations and simulations using CCM2 forced with ARM data**

**Difference between observations and simulations using CCM2 forced with processed data using variational scheme**

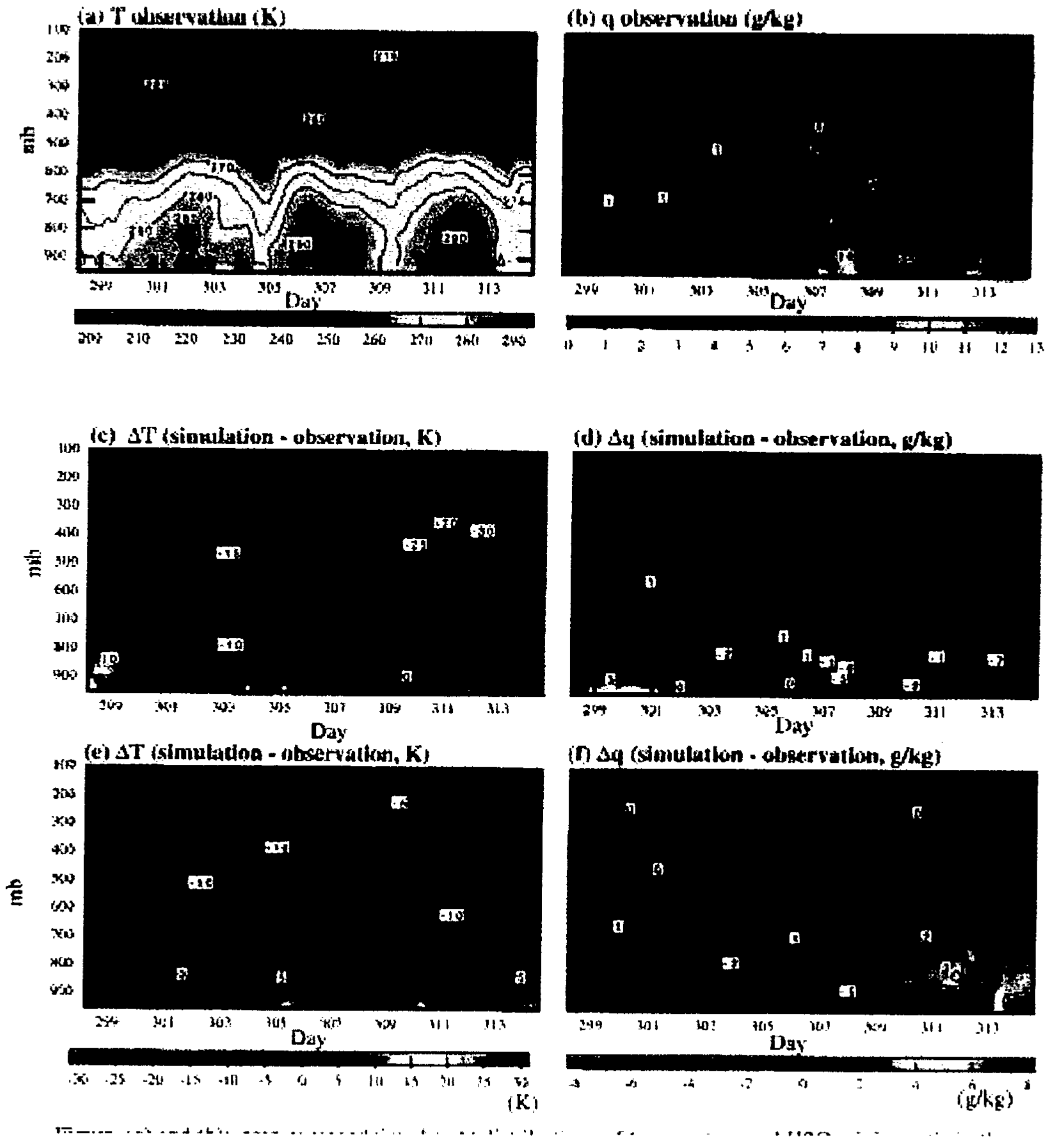


Figure 5:

We note, though, that the needed constraint data are only available during the IOPs. It is not clear to us that one can understand the site behavior well enough from the deployed instrument density and instrument configuration to obtain useful data at other times. Additionally it seems that such a description would in general require field information on a spatial scale that is much larger than the ARM SGP site, because the needed coverage is dictated by the scale of convective transport into the grid box of concern. Hence, it is likely that obtaining such data will involve campaign-style measurements and/or coordinated satellite data collections. If this is indeed the case, it is problematic for the ARM sites and site operations as currently configured to obtain a meaningful time series of such observations for the SCM modeling purpose. Clearly this issue should be addressed so that resources are devoted towards collecting a time series of data that can lead to closure on problems of concern, given the budgetary constraints and the other usual constraints associated with prioritizing instrument deployment and operational time for any program of the size and scope of ARM.

## 2.4 "Active" Experiments

In addition to the "observatory" mode that ARM has been working in to date, we suggest another possible line of experimentation for consideration. A fundamental aim of the ARM program is to understand and describe clouds well enough to predict relevant "local" changes (cloud albedo, absorption, rain-out, etc.) when climate model input parameters are varied. The program to accomplish this is based mainly on observing as much as possible with existing ARM site instrumentation about clouds and cloud changes as naturally occurring meteorological conditions vary over an ARM site. If accurate physics/chemistry – based cloud modeling were achieved it should,

of course, be able to predict quantitative consequences for clouds of anthropogenetically initiated meteorological changes as well as natural ones.

For example, old fashioned cloud seeding by NaI crystals spread from a small airplane would affect droplet formation and rain-out in ways that should be calculable from a successful ARM cloud model. Such experiments may be a useful adjunct to present data collection.

Electric power plants stacks are a source of $SO_2$ together with some $H_2S0_4$. If they happen to be sited appropriately, release rates could be controlled to give some episodic emission changes. These could affect meteorological variables over a nearby SGP ARM site in two ways.

(1) When enough oxidant is available (as certainly expected in summer) most of this $SO_2$ will end as atmospheric sulfates. About half or so might add to the size of the ambient air's sulfate aerosol particles. Much of this could increase albedo above the ARM site in a calculable way, depending upon time of day, winds, etc.

(2) More important and relevant would be the added sulfate's contribution to more or larger local cloud condensation nuclei and to the added acidification's reduction in the size of the smallest growing droplets over the ARM site. A successful ARM cloud model should be expected to give reliable predictions of consequent cloud changes to compare to ARM observations.

# 3 COUPLING BETWEEN ARM AND CLIMATE/WEATHER MODELING EFFORTS

The JASON study also attempted to address whether the ARM data were being utilized by the modeling communities who are in fact some of the ultimate customers for such measurements. It is useful to divide such interactions into classes characterized by the type of modeling that is being supported: climate modeling, weather modeling/forecasting, and cloud system modeling. Each different type of modeling/ARM interaction is discussed in some detail below.

## 3.1 Interactions between ARM and the Climate Modeling Community

Based on discussions with climate modelers and climate modeling groups who were consulted during the course of the JASON study, there clearly is a less than optimum connection between the ARM data and the climate modelers. For perspective, the ARM data are not widely regarded in the climate community as the human genome project data was to biologists: a widely awaited data set that would forever change the way the entire field performed its work. There are a few notable exceptions to this generalization about the ARM/climate modeling community interaction, for example Tony Del Genio of NASA/GISS (whose efforts to incorporate ARM-compatible cloud parameterizations into GCM's have been discussed above) and Jeff Kiehl of NCAR. Both Del Genio and Kiehl are ARM-funded, and this fact may be instructive as well.

There are several possible reasons why the coupling between climate modelers and ARM data is not stronger. One of these might include the

perception of the climate modelers that the ARM data are not important to current GCM improvements, in that the models have so many other acknowledged deficiencies that forging agreement with ARM data is not considered to be a high priority at the present time. A second reason might be that the ARM data are not in a format that is considered useful to climate modelers, who are not especially interested in the magnitude of a radar return but instead want cloud fraction and cloud height, for example, as properties with which they can develop and/or validate GCM parameterizations (see the section on Value Added Products below for more on this point). A third possible reason is that the ARM data sets might not be complete enough, either in spatial or temporal extent, to be useful to GCM modeling efforts. A fourth reason might be that climate modelers perceive that the highest leverage, and most significant improvements in GCM performance, will come about in the short term through access to improved computational capabilities and through improved algorithmic coding of the GCM's, and therefore they focus on the computational aspects of modeling rather than improving the parameterizations of the existing GCM's.

In contrast to ARM data, the latest satellite products are greatly anticipated by the climate modeling community. Simply put, when interested in developing parameterizations as opposed to the underlying fundamental physics, global coverage is far more useful to a climate modeler than the time series over a small (on a global scale) spatial region that is produced by an ARM site.

Additionally, there are 6-12 different climate models, and these models differ from each other in many different ways. ARM data do not now form a key differentiator or validation metric for these GCM's. In the larger view, it is difficult to decide objectively whether a new model is better than an older model, if both the new and old models are in error in different

ways with respect to different sets of observations. Furthermore, in certain cases, improved local parameterizations that have resulted from agreement with ARM data have been rejected for use in GCM's because including such smaller spatial-scale improvements without following through on the highly labor-intensive task of accounting for the propagation of such changes on all of the other parameterizations of a GCM generally produces larger-scale failings of the resulting model with respect to commonly-used GCM model validation metrics. In brief, differing modeling groups may differ on the fundamental question of what constitutes a good model!

The above reasons might be interpreted to suggest that ARM should simply continue its data collection efforts and wait for the GCM modeling community to come around to using these data when they decide it is important to do so. However, in our view ARM would benefit from interaction with the modeling community at least as much as the modeling community would benefit from interaction with ARM. Specifically, information on sensitivity to specific parameters is critically needed to help direct ARM measurement efforts and experimental design. For example, if one can only measure clear sky radiative forcing to 5 $W/m^2$, what is the uncertainty in GCM predictions in response to a doubling of $CO_2$ (equivalemt to 4 $W/m^2$ increased forcing)? Which types of measurements, and at what spatial density, are required to close the boundary conditions for single column models (SCMs)? What quantities should be of the highest priority to drive IOP's at ARM sites for investigation of cloud parameterizations? Where should additional sites be located, and for how long, to best foster interactions between the ARM data and the GCM models? These issues can be addressed within models and would strongly inform ARM experimental design. The climate modeling community should be encouraged to conduct such sensitivity studies.

Finally, interaction with the modeling community should in principle aid ARM and the larger climate observational efforts to formulate a data collection program that ultimately would critically challenge, and either improve and/or invalidate, competing models based on agreement (or lack thereof) with observational data.

Among the various options available for ARM are these:

a) do nothing;

b) have ARM develop and run its own climate model,

c) have ARM partner closely with an existing climate modeling group.

Option a) has been discussed above and is not very palatable. Option b) is even more unsatisfactory, because developing a GCM is a time and labor-intensive endeavor that would certainly consume (needlessly) a significant fraction of the ARM resources for many years to even become equivalent to efforts that already exist in the major climate modeling centers either in the U.S. or internationally. Hence the preferred path is option c): partner with and co-sponsor, an existing climate modeling group that develops and runs GCM's. One approach to creating such a partnership is to have the ARM program produce a request for proposals (RFP) for GCM runs devoted to sensitivity studies and instrument deployment and siting issues that face the ARM program directly. In this fashion, at least, ARM would initiate the coupling process to the modelers and get some of what it needs in the way of analysis information from the GCM community.

Though the political "climate" may make it difficult, there may be value in establishing a climate center which includes both well planned and executed observations such as ARM, substantial modeling coupled to these experiments, and close coupling to global, satellite-based, observations. Whether

DOE should take the lead in such an effort or whether it should be a co-operative effort of the U.S. Global Change community should be carefully considered. At minimum it must accomplish the goal of closely coupling the observations with climate modeling, which is now quite weak.

## 3.2 Interaction between ARM and Numerical Weather Modeling/Forecasting

Weather forecasting and weather modeling are inherently better matched to the spatial and temporal scale of the current ARM observational capabilities than is climate modeling. Recognizing this fact, ARM has fostered a significant interaction with Christian Jakob of the European Center for Medium Range Weather Forecasting (ECMWF). The ECMWF finds ARM data useful for improvement of their weather forecasting capability, and therefore ECMWF is interested in interacting with the ARM data and with ARM personnel. We provide some specific technical comments on the interaction below and then present general remarks concerning this interaction with the ARM program in the future.

### 3.2.1 "Data Assimilation" And "Assimilation Of Data"

Short range forecasting and climate prediction using models of the Earth's ocean and atmosphere pose two similar, yet separate, challenges to numerical implementation. Short range weather forecasting requires, in addition to an accurate model, an accurate version of the initial state from which the forecasting is to begin, and what is called a "balanced" state in which the effects of high frequency short wavelength wave phenomena are minimized by an effective projection onto a low frequency submanifold of the very high

dimensional state of the model. Climate prediction is an effort to determine the statistical behavior of orbits on the attractor of the atmosphere/ocean system regardless of knowledge of the precise initial condition from which the model is run, assuming that the system is not multistable and that the initial condition is within the basin of attraction of a climate of interest.

As part of the plan for the ARM science program, it was suggested by Tom Ackerman and Dave Randall (JASON briefings, June, 2001) that one pursue what Randall called ITEA: initial tendency error analysis. By this he means "numerical weather prediction (NWP) is an excellent way to test an atmospheric model against data. It is not a sufficient test for a climate model, but it is a very valuable test." He attributes to B. Machenhauer and colleagues "the proposal that the analysis of initial tendency errors can help isolate deficiencies in parameterizations." The model is initialized using observations, and the computed initial tendencies are compared with the observed tendencies. This is repeated many times, for different weather situations, and systematic errors are detected by averaging. The systematic errors are then attributed to specific aspects of the model's formulation, *although exactly how this can be done has not been clearly spelled out.* Another approach is to focus on regions for which excellent supplementary data are available. This is where ARM comes in.

We heard from Christian Jakob of EWMCF about the importance of ARM data in improving this group's forecasting capability. In his talk he also discussed "data assimilation", which has a very special meaning in the NWP/climate modeling world (see Appendix A). ARM data are useful in obtaining a better description of the initial state of the system, which can be used to make better weather forecasts. We discuss in more detail in Appendix A some technical aspects of how this procedure can be modified and improved further to additionally produce better weather models. However,

the improvement of weather forecasting capabilities is certainly a good use, albeit perhaps not mission-critical application of ARM data.

### 3.2.2 General Comments on Interactions Between ARM and Weather Modeling Efforts

The discussion above and especially in Appendix A is primarily focused on how ARM data can be used to provide improved capabilities for weather forecasting. This is, of course, of significant benefit but is not necessarily relevant to improving climate models. In the short term, the contention is that one can validate GCM's by running them in a weather prediction mode and evaluating their initial tendency error analysis. However, it is not clear to us that a good climate model is a good weather model (or vice versa). For example, initially the European weather model, when forming the basis for the German climate model, made a poor climate model (e.g. weather model drifts may be unimportant for weather forcasting but unacceptable in climate prediction models). Such a comparison would tend to emphasize what weather models do well, as opposed to radiation and hydrology budgets, which such models typically treat poorly. In addition, there is an inherent assumption that the high frequency modes that drive the weather are well coupled to the lower frequency modes that drive climate. The validity of such an assumption is not at all clear at the present time.

In the short term, therefore, it appears that the interaction between the ECMWF and ARM will be of primary benefit to obtaining improved weather forecasting and weather models (which may well be of high benefit in itself to U.S. weather forecasting capabilities if it were exploited by the U.S. National Weather Service). In contrast, in the long term, if ECMWF adds an ocean model to produce a GCM, as they have indicated they will need to do as they proceed with extended (30 day or greater) range weather

forecasts, they might be the ideal/needed partner who develops a GCM in close relationship to the ARM data and ARM-related parameterizations.

## 3.3 Interaction Between ARM and Cloud System Models

Cloud system (or cloud-resolving) models also present an opportunity to foster interactions between the modeling community and the ARM data. In fact, this might be the best opportunity for interaction in the short term that is available to the ARM program to further climate modeling efforts. We discuss various aspects of such interactions below.

Cloud system models (CSMs) are $(2 \times 2)$ km$^2$ resolution models for use in a GCM's $(> 200 \times 200)$ km$^2$ resolution grid box. In a CSM, $N^2 = 10^4$ CSM columns are represented by one two dimensional single column model (SCM) in a GCM (Figure 6). Clearly some parameterization needs to be performed to allow such a CSM to be incorporated into a GCM.

In an illustrative and typical approach one takes N (x-averages) and N (y-averages) of the CSM, and therefore 2N parameters for each GCM grid box, instead of passing $N^2$ parameters onto that same sized grid box (a number far too huge to be accommodated in GCMs, limited by present computing power). The choice of which parameters to pass on and how to compute them is somewhat *ad hoc* at the present time.

We heard a presentation by Dave Randall in which it was claimed that CSMs yielded an improved description in a GCM grid box scale, as validated by ARM data, relative to a single column model that would be used in a GCM. However, there may be a question about whether the CSM was tuned to describe the particular data set(s) for which it was evaluated. There were

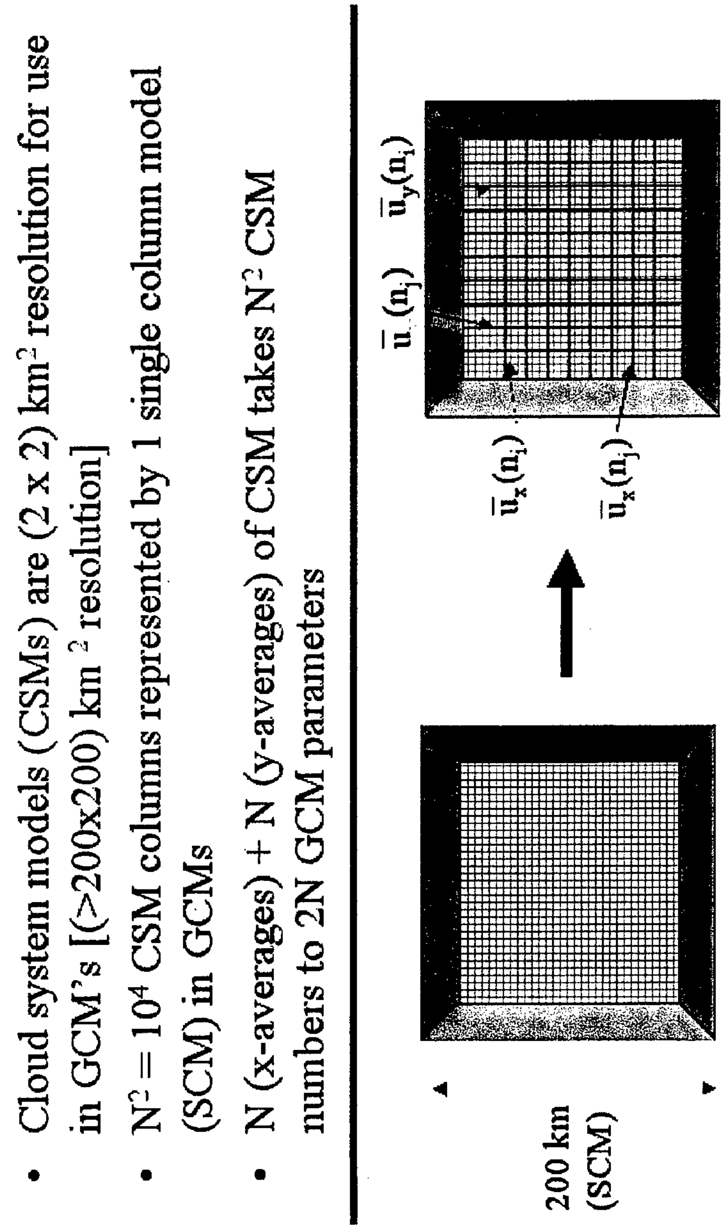


Figure 6: A schematic explanation of the basic approach to developing a Cloud System Model (CSM).

not enough precisely-determined observables to allow the initial state of the CSM to be well-determined at the full CSM resolution. Hence there must be some near GCM-scale parameterizations imbedded in the improved CSM. Consequently, CSM's could be useful to discover these improved parameterizations for use in GCM's (but not run at CSM resolution). Additionally, ARM data could be useful to help develop improved CSM's, and extraction of such improved parameterizations could then be used to obtain improved GCM's. Finally, feedback with the model could aid in the formulation of ARM instrument deployments.

The use of a CSM is an attempt to somehow incorporate smaller grid scale features into a GCM. Currently the scale of a GCM single column model (grid box) SCM scale is determined by existing computational limitations on GCM's. It is useful, in contrast, to ask on what scale does modeling need to occur in order to capture the physical properties that drive the system? Indeed the long history of trying to describe quantitatively classical turbulence where large scale eddies interact with small scale eddies which they feed does not lend confidence that gross parameterization from GCMs of smaller scale meteorological processes will be achieved easily or quickly.

# 4 INSTRUMENTAL AND OPERATIONAL ASPECTS OF ARM

In this section, we discuss several programmatic aspects of ARM in response to specific requests in the study charge to JASON on the ARM program.

## 4.1 Instrumental Operations

We believe that operation of the instrumentation on a continuous basis is a major accomplishment for the ARM program. It represents a significant departure from the traditional modes of operation of the climate data collection community, which has typically emphasized campaign-style observations (with no historical record), satellite data (with no concentration of instrumentation onto the same physical location), meteorology-based observational programs (that are not of the needed accuracy or stability for climate-related data collection), or examination of the historical record (such as the temperature records in a specific city, positions of glaciers, etc.). In this respect, the ARM program to date has been a resounding success.

## 4.2 Access to ARM Data

The ARM data are routinely accessible even to the novice in a straightforward fashion. Accessing the URL http://www.arm.gov readily leads one to the data archive section, and allows easy access to basically any data set of particular interest. The ARM archive contains over 12 Tb of data in over

800 data streams, and is being accessed at an increasing rate by the general user community. In this respect, the ARM program is exemplary.

## 4.3 Satellite Calibration/NASA Interactions

The ARM sites are now used routinely by NASA for satellite calibration and retrieval algorithm development. Specifically, all three of the ARM sites are primary ground validation locations for the MISR (Multi-angle Imaging SpectroRadiometer), CERES (Clouds and Earth's Radiant Energy System), and MODIS (Moderate Resolution Imaging Spectrometer) instruments, on the EOS-1 (TERRA) satellite platforms. Additionally, the three ARM sites are slated to be primary validation locations for the MODIS and AIRS (Atmospheric Infrared Sounder) instruments on the EOS-2 (AQUA) satellite. Additionally, AIRS will pay ARM for sondes launched at ARM site overpasses by their satellites for validation purposes. Finally, ARM is planned to be a ground validation site for the upcoming CLOUDSAT cloud radar satellite to be launched by NASA. Again the ARM team is to be complimented for interactions across agencies in a coordinated fashion to make use of its capabilities in a complimentary fashion to that of the NASA satellite effort for monitoring global change.

## 4.4 Future Site Capabilities and Siting Issues

The operational suite of instruments at the existing ARM sites is clearly of value for certain problems, as discussed in more detail in the sections above. Moving forward, ARM needs to decide whether its highest priority future focus is climate monitoring or model parameterization validation. Climate monitoring requires daunting accuracy in the radiation budgets. Changes

of 1 K correspond approximately to radiative flux changes of 4 $W/m^2$ so one might need an accuracy and stability of $<0.4$ $W/m^2$ in radiation measurement for climate monitoring purposes, which apparently is well beyond the existing instrumental capabilities. Can such accuracy be achieved using best-available methods? If not, how seriously will this limit model validatio and climate prediction and monitoring? The sites should also be viewed as prototoypes for future observing stations instead of permanent, fixed configuration installations. The sites could also be used to test how well the main ARM site data and models can in fact describe the atmospheric column in a GEM grid cell. The right mix of number of sites and site capabilities needs to be carefully explored; perhaps a much larger number of sites, with each site being much less expensive and differently instrumented, would better serve the overall ARM programmatic goals with respect to climate observation. If ARM were to give a high priority to climate monitoring it must certainly have a very large number of sites to differentiate between slight geographical shifts and shifts in time.

ARM has developed three sites, each of which is subdivided.

**Southern Great Plains (SGP)** : Located in north-central Oklahoma and south-central Kansas, this is the first and major ARM site. It has been operating since 1994, and now has very little down-time for its primary systems. The data systems and site mangement are located at the Central Facility, but some measurements are repeated at the Boundary Facilities.

Central Facility
Boundary Facilities (6)
Extended Facilities (26)
Intermediate Facilities (3)

**North Slope of Alaska (NSA)** : Located to sample the Arctic,

- Barrow is the northernmost village in Alaska, 71.2°N, 156.6°W, and is adjacent to the Chuckchi Sea. It began operating in late 1997. NSF and NOAA have nearby facilities. One of the CART systems, hardened to withstand the weather, is installed here. In 1999 the SHEBA project installed facilities on nearby pack ice to study heat transfer through open leads.
- Atqasuk 70.5°N, 175.4°$W$ is south and inland from Barrow and has the equipment left from SHEBA.

**Tropical Western Pacific (TWP)** : Designed to sample the Warm Pool in the western Tropical Pacific, this site started operating in 1996. Defined by water surface temperatures greater than 28°C, the Warm Pool generates intense convective systems. Disruption of the normal regime over the Warm Pool, termed La Nina, moves much of the warm water eastward to begin the El Nino regime.

- Manus is a large (30 km by 80 km) island north of New Guinea at 2°S, 147°E. It has the first Atmospheric Radiation and Cloud Station (ARCS-1). During La Nina conditions, Manus is well within the Warm Pool.

  The site is actually on the small island at the eastern end, near the airport, but, in view of the concerns regarding the island effect at Naru (below), how well the site represents conditions in the surrounding ocean should be evaluated before the system is operated much longer.
- Naru, a small (4 km diameter) island at 0.5°S, 167°E. The site has been operating since late 1998 and has ARCS-2. There are concerns about the effect of the island on local clouds; several

studies of the island effect are mentioned on the web site. During a month-long Intensive Observational Period (IOP), Naru99, two ships held station upwind to form a triangle with the island. Presumably one objective was to compare the statistics of cloud properties at the three stations to assess the island effect on the Naru observations. The results of Naru99 should be viewed as a test of the site and whether it can meet the original objective of being representative of the eastern edge of the Warm Pool in the western Pacific.

- Darwin, in northern Australia, will be developed in conjunction with Australia by installing equipment that had been used to test instrument modifications at SGP.

Before sites are made 'permanent' or even continued for many more years, they should be evaluated to determine:

- Are the sites in the best places to meet the objectives set for them?
- Are the locations suitable for comparing with outputs of weather and climate models? In particular, should small arrays of key sensors be used to approximate the spatial scales of model products?
- Do they have the right sensors? Are there automated systems that can obtain some of the profile data now acquired by balloons?
- How can down time at the remote sites be decreased?
- We note that 60% of the operational budget is consumed by the TWP site. Is it returning proportionately as much scientific data value as is being expended on it?

- There is also a case for some open ocean sites, as distinct from coastal sites. One should then think of a moveable platform. Two possibilities are towed platforms or moored observing stations. The DEOS program is planning to provide for the latter in several years. Available power is about 1000 watts, and there is provision for satellite data readout. Space will however be a problem. Can a reasonable ARM site be confined to an area of 5000 square feet?

One would also like an isolated island site, a site to probe the effects of forests (Costa Rica), and a southern hemisphere site. Potentially the sites could be cooperatively located with the assistance, both logistical and financial, of other countries; an example of what is possible is the IMS collection of sites for monitoring the nuclear test ban treaty that is being deployed globally and supported in a coordinated international fashion. It would seem that a similar international arrangement ought to be possible for climate monitoring facilities as well.

## 4.5 Value Added Products

Value added products (VAPs) are the conversion of primary data into data products useable by others, e.g. GCM model makers. These include, for example, coverting radar returns into cloud fraction, cloud height, etc. ARM is undertaking significant efforts to produce such value added products both to enhance the value of the data to its own user community and possibly to entice climate modelers utilize the ARM data more readily. These efforts prompted several comments from JASON.

Formulation of value added products is in general, of course, a good idea. Collecting the data without providing it in a format that can be used

by others does not fulfill the mission of the data collection entity. Nevertheless, providing the value added products contemplated by ARM necessarily requires input from the user community of these data products. The danger is that the secondary quantities (the data products) become "gospel" and are removed from important relationships to other primary data. Because one of the primary purposes of the ARM time series is to validate and/or formulate improved parameterizations based on functional relations that may not be known in advance of the data collection, this consideration is critical to successful implementation of a VAP program from the ARM data. Optimally the formulation and prioritization of value-added product would be driven by motivated "data customers", who in this case would be the various modeling communities. However, interactions with the GCM community currently suffer from the barriers to incorporation of ARM data that have been discussed above. We note, however, that the development of the desired data products would be a natural outcome of a two-way interaction that would result from partnering between ARM and a climate modeling group.

# 5 CONCLUSIONS

Based on the detailed discussion above, we offer the following conclusions in response to the study charge.

1. ARM is meeting its charter in fine fashion. ARM provides a needed focus on fundamental understanding, at various levels, of atmospheric radiation/transport interactions in the overall climate change effort both nationally and internationally.

2. The benefits of strong scientific leadership are clearly evident. The ARM team and its leadership are to be commended for the progress and accomplishments of the ARM program to date.

3. ARM is best-suited for addressing issues that are well-matched to the ARM site space/time scales, specifically:

   a) Clear sky radiative transport

   b) Radiative transport properties of various types of clouds

   These types of activities should continue at the various sites until the issues at hand are brought to closure scientifically.

4. ARM plays a valuable role in providing ground truth for various NASA satellite instruments.

5. ARM appears to be well-suited for evaluating cloud parameterizations in diagnostic/validation mode. Data from multiple ARM sites will likely be needed to significantly impact this area, however, and such efforts should be expanded in the future.

6. ARM appears less well-suited for closing boundary flux problem in support of single column modeling. A better understanding of the instrumentation density, siting, and system scaling behavior is required to assess how much effort should be made in support of this goal.

# 6 RECOMMENDATIONS

We present the following key recommendations regarding future directions and evolution of the ARM program.

1. *ARM needs as a program to decide whether its future focus is process oriented parameterization validation or climate monitoring, and configure its observational efforts and science team focus accordingly.*

   The climate community seems to agree on the lack of 'climate data' and the crucial need for it in the future. By 'climate data,' they mean long-term observations of the 'right' variables with sufficient accuracy and spatial coverage to assess variability over time intervals of decades and longer. Nearly all present meteorological observations are designed as inputs for numerical weather prediction and may lack the accuracy needed for the much longer climate time scales. Concentrating on how and where to collect climate data about radiation and cloud properties should remain the primary focus of ARM. It has done an admirable job so far, and it should certainly keep and continue a strong science base for its measurements, but much remains to be done with the measurements and that is ARM's unique responsibility.

   Parameterizations are moving targets because they depend crucially on the spatial grid and time steps of the models using them. ARM should concentrate on understanding the underlying physics and measuring the key variables that are need to assess long-term trends in the atmosphere and to test models having much better resolution than are available today.

2. *More extensive interactions with the modeling community is needed, especially towards the goal of facilitate modeling work in support of ARM*

*needs, such as sensitivity studies and assessment of optimal instrument configurations and siting.*

In parallel with ARM, DOE started CHAMP to spur computing hardware for climate models. CHAMP led to the current DOE modeling effort, CCMP. It seems to be time for DOE to focus its modeling efforts into a program that can work with ARM and address the issues the ARM team have identified, or to aid ARM in bridging its data collection efforts to another agency's or country's program in climate modeling. Without a more focused approach, U.S. climate modeling is likely to remain much less than it can and should be.

3. *Additional sites should be carefully evaluated with respect to cost/benefit analysis towards future goals. A mobile site seems to be a high priority, and international cooperation on siting and site operations is highly desirable.*

   Before any sites are made 'permanent', their suitability for comparisons with models should be examined. Should ARM shift their measurements to distributed systems over approximately the same spatial scales as models now deal with? Is the TWP site returning data of a value commensurate with the funds expended to operate it? Should the next site be a mobile site as opposed to another fixed site?

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# A APPENDIX

## A.1 Data Assimilation Methods for Improvement of Models

The modelers assume that there is a model that they know precisely. It operates in a D-dimensional space moving a state vector $x(t)$ about in time according to a known model $\frac{dx(t)}{dt} = f(x(t), \mu)$. $\mu$ is a set of parameters, some of which may be associated with knowledge gained at the ARM site(s). The flow in continuous time is replaced in reality by a discrete time map implemented as an ordinary differentiate equation (ODE) solver of some sort, usually sophisticated. We continue by talking only about finite time maps taking $x(n) = x(t_0 + n\tau_s)$ with $t_0$ some initial time for a calculation and $\tau_s$ the step size. The dynamics is now a discrete time map $x(n+1) = F(x(n), \mu)$.

Once the modelers have selected a model, they argue that the predictive capability of the model is associated with their knowledge of the initial state $x_0$. Now they make a set of observations $s(0), s(1), s(2), \ldots, s(N), \ldots$ which have errors due to noise or whatever. They want to use these observations to establish the "best" initial state $x(0)$ associated with the model and with the observations. To this end they use an optimization principle that is based on a "cost function," typically a least squares expression. This is a function of the sequence of observations $S = \{s(1), s(2), \ldots\}$ and the unknown model states $\{x(0), x(1) = F(x(0), \mu), x(2) = F(x(1), \mu) = F^2(x(0), \mu) = (F(Fx(0), \mu), \ldots, x(n) = F^n(x(0), \mu)\}$ which depend on $x(0)$. A typical cost function could be of the form

$$J(x(0)) = \frac{1}{2}\sum_{l=1}^{L}(s(l) - x(l))^T R^{-1}(s(l) - x(l))$$

$$= \frac{1}{2}\sum_{l=1}^{L}(s(l) - F^l(x(0)\mu))^T R^{-1}(s(l) - F^l(x(0), \mu))$$

where $R$ is an estimate of the error covariance matrix for the deviation of the observations from the model results. Varying $J$ with respect to $x(0)$ will produce an improved $x(0)$ from which further prediction can proceed. This is called "data assimilation" in the numerical weather prediction community.

This procedure does not use the observed data from ARM or other sources to improve the values of the parameters $\mu$. To achieve that, still keeping the functional form of the model intact, we follow an idea of Smith and McSharry, which provides an optimization principle independent of $x(0)$ but dependent on $\mu$.

The idea uses the fact that for a map of the form $x(n+1) = F(x(n), \mu)$ which is dissipative, as all weather or climate models are, the set of states visited by the system after some initial transients is a compact geometric figure in D-space called an attractor. For this to be precise in the presence of time varying forcing functions, the state of the system must include specification of the forcing as well.

All initial conditions within a certain *basin of attraction* visit the same attractor, but in a dramatically different temporal order that is sensitive on $x(0)$. There is a natural density on this attractor that tells us how often the orbit visits a volume of D-space. This natural density $\rho_\mu(y)$, where $y$ is a vector in the D-dimensional space, is given by

$$\begin{aligned}
\rho_\mu(y) &= \lim_{k\to\infty} \frac{1}{K}\sum_{k=1}^{K} \delta^D(y - x(k)) \\
\rho_\mu(y) &= \lim_{k\to\infty} \frac{1}{K}\sum_{k=1}^{K} \delta^D(y - F^k(x(0), \mu)).
\end{aligned}$$

In practice, of course, $K$ is large, not infinite, but the quantities we are interested in will reach their large time values as 1/K, so this may not be critical.

If one really wants to work with the natural density $\rho_\mu(y)$, we cannot use mathematical delta functions $\delta^D(y - x(k))$, but we have to replace this with something strongly peaked near $y \approx x(k)$ and with integral unity. The Gaussian $\frac{e^{\frac{-(y-x(k))^2}{\sigma^2}}}{\sqrt{\sigma\pi D}}$ is a good choice, though many others will do.

The actual evaluation of $\rho_\mu(y)$ is daunting when $D$ is large, but it may be that there are $D$ effective degrees of freedom which is smaller than the total very large state space dimension embodying all the dynamical variables (wind, temperature, humidity, ..) at all spatial locations. If so, evaluation of $\rho_\mu(y)$ may well be interesting.

Any function $g(y)$ on the D-dimensional state space when integrated with $\rho_\mu(y)$ to get its average over the attractor is independent of $x(0)$. Strictly speaking we let the system evolve from the actual initial state for a short time until transients are gone, at that time, select a state which we call $x(0)$ and then study the dynamics from that instant on. The idea is that an arbitrary initial state in the basin of attraction of the model attractor will be attracted to the attractor, and the state $x(0)$ we select is "on the attractor".

Define

$$\begin{aligned}\bar{g}(x(0)) &= d^D y g(y)\rho_\mu(y) \\ &= \frac{1}{K}\sum_{k=1}^{K} g(x(k)) \\ &= \frac{1}{K}\sum_{k=1}^{K} g(F^k(x(0),\mu))\end{aligned}$$

where $K$ is large. This is the natural average of $g(y)$ over the attractor weighted by the normalized frequency $\rho_u(y)$ at which an orbit visits various parts of the attractor. Now consider another initial condition in the state space which after transients arrives at $X(0)$ on the attractor. Since both $x(0)$and $X(0)$ are on the attractor, one can reach one from the other by a finite number of time steps using the dynamics $y \rightarrow F(y,\mu)$, so $X(0) =$

$F^L(x(0))$, or $x(0) = F^{-L}(X(0))$, for some integer $L$.

$$\begin{aligned}
\bar{g}(x(0)) &= \frac{1}{K}\sum_{k=1}^{K} g(F^k(x(0),\mu)) \\
&= \frac{1}{K}\sum_{k=1}^{K} g(F^{k-L}(X(0),\mu)) \\
&= \frac{1}{K}\sum_{k=-L}^{K} g(F^k(X_0)) + \sum_{r=1}^{K} g(F^r(X_0)) - \sum_{r=K-L+1}^{K} g(F^r(X_0)) \\
&= \bar{g}(X(0)) + O(\frac{1}{K}).
\end{aligned}$$

For each value of $\mu$ we integrate the for a long enough time to determine $\rho_\mu(y)$. These distributions we record, once and for all. Now we take a cost function and average it over the attractor using $\rho_\mu(y)$ as a weight in the average. This average will be independent of any initial condition and will be a function of the observations entering the cost function and the parameters.

By the way this argument suggests that if $L$ is too large in the cost function $J(x(0))$ above, it will be essentially independent of $x(0)$ and thus a very inaccurate way to determine an initial state.

Among the parameters which determine the model $F(y,\mu)$ are the boundary conditions for the partial differential equations which are being approximated by spatial and temporal sampling. One could actually test whether the average of interesting functions $g(y)$ integrated with $\rho_\mu(y)$ is independent of $x(0)$ by solving for $x(n)$ for specified boundary conditions and examining the independence of $\bar{g}(x(0))$ on $x(0)$.

Here is an example of a cost function that might be useful. It follows Smith and McSharry.

$$C(S,y,\mu) = \prod_{m=1}^{m=N-1} e^{\frac{(s(m)-y)^2}{\sigma_1^2} + \frac{s(m+1)-F(y,\mu))^2}{\sigma_2^2}}$$

$\sigma_1$ and $\sigma_2$ are resolution errors at each step.

Minimization of this cost function associates each observation $s(m)$ with a location $y$ in D-dimensional state space and jointly associates with the next observation $s(m+1)$ the location into which $y$ *goes under one step of the model* $y \rightarrow F(y,\mu)$. So minimization of this cost function says that if an observation $s(m)$ is near $y$, then the next observation $s(m+1)$ must be near $F(y,\mu)$.

If we average this over all $y$ with weights $\rho_\mu(y)$

$$M(S,\mu) = y\rho_\mu(y)\, C(S,y,\mu)$$

then minimizing $M(S,\mu)$ gives us an optimization principle for the parameters which evaluates the cost function **only** on the states allowed by the dynamics $y \rightarrow F(y,\mu)$ <u>and</u> is independent of the initial state of the system. In effect, $\rho_\mu(y)$ contains all information about where the state can go for each selection of parameters values.

Now we can use this cost function, clearly one of infinitely many one could select, as a principle on which to select the parameters for the model based on the information in the observations $S$. The idea is that we somehow have gotten the model for clouds, radiation transfer, convection,... all correct in form but still are uncertain about the particular numerical value of some of the parameters we need for the model to correspond to our atmosphere and oceans. Adjusting the parameters in a manner independent of the initial condition of the model and thus of the detailed evolution of the states of the model is provided by the cost function $M(S,\mu)$.

Suppose one has selected parameters, say for a cloud parameterization for the ARM SGP site. The minimization of $M(S,\mu)$ involves varying only those parameters and leaving all others, presumed known well enough, fixed. Then in normal language we would say we have, within the class of models adopted, assimilated the knowledge from the sequence of observations $S$.

This is assimilation of data and is independent of the initial state of the system.

With parameters set, the model $F(y, \mu)$ is "finished." To predict accurately one now uses the numerical weather prediction/climate modelers "data assimilation" to determine that initial state $x(0)$ for the model which best, according to "standard" criteria, gives the closest sequence $\{x(1), x(2), \ldots, x(N)\}$ to the observations. This may use an ARM time series as the observations $S$ at the GCM grid point associated with the SGP or TWP or NSA site, but no further adjustments to the "physics parameters" $\mu$ are made at this stage.

The "cost function" used at ECMWF is according to Jakob

$$\begin{aligned} J(S, y, \mu) &= \frac{1}{2}\sum_{n=1}^{N}(s(n) - F^n(x(0), \mu))^T \cdot R^{-1} \cdot (s(n) - F^n(x(0), \mu)) \\ &+ \frac{1}{2}\sum_{n=1}^{N}\sum_{k=1}^{K}\frac{g(F^N(x(0), \mu)) - g_{0k}}{\sigma_{0k}} \end{aligned}$$

where $x(n)$is the state vector including temperature, pressure,..., $s(n)$ is the observation at time $n$, $R$ is the background error covariance matrix as above, $\sigma_{0k}$ is the observation error, $g_k(x(n) = F^n(x(0), \mu))$ is the observation operator which translates observations of state variables into fluxes of radiation and descriptions of clouds, and $g_{0k}$ are the observations of these fluxes. The first part of the cost function constrains the state of the system to be near the observations, and the second part does the same for important functions of the state.

Various cost functions are formulated which have as a goal the determination of an initial state $x(0)$ which allows the states determined by the model $F^n(x(0), \mu)$ to remain as close to the observations as possible.

Since the evolution of the model system $x(n-1) \to x(n) = F^n(x(0), \mu)$ is nonlinear and certainly chaotic, there is a limit to how far in advance one

can reliably use such a cost function to determine $x(0)$ as information on the initial state is lost exponentially rapidly in such a situation.

Fortunately one can determine the limits on this procedure directly from the model itself, as we have announced it is precise, all parameters having been adjusted to conform to the statistical behavior of the system. For this one needs to determine the largest Lyapunov exponent of the model $x(n) = F(x(n-1), \mu)$ using standard methods. The determination of the largest Lyapunov exponent $\lambda_1$ is rather numerically insensitive to method, so one can expect it to be easy to evaluate. Any error $\Delta x(0)$ in the initial state will now grow approximately as $\Delta x(t) = \Delta x(0) e^{\lambda_1 t}$ , so the largest time for which one may use data to determine the initial state is approximately

$$T_{\max} \approx \frac{1}{\lambda_1} \log \frac{R_A}{|\Delta x(0)|}$$

where $R_A$ is the "size" of the attractor. This says that when the error in the initial state grows to be the size of the attractor, all prediction is uncertain. Another prescription allows the initial error to grow by a factor $R > 1$, and limits prediction (or looking backward to the initial state) by this, so

$$T_{\max} \approx \frac{1}{\lambda_1} \log R\,,$$

This discussion suggests that the ITEAs recommended by Machenhauer and Randall are not appropriate if improving parametrizations is the desired goal. To "assimilate the data" one relies on statistical quantities **independent of initial conditions** $x(0)$. The forecasts suggested in ITEA are not such quantities. The averaged (with $\rho_u(y)$) cost functions are such quantities. ARM time series observations can then be used to determine a good initial state $x(0)$ from which to make accurate forecasts.

The problem with comparing "tendencies" from different initial states is that one can only make short term forecasts, for times shorter than $T_{\max}$,

and attractors are not homogeneous, so the "tendency" depends sensitively on the initial state $x(0)$, the location on the attractor from which it starts. Furthermore the suggestion of simply averaging such "tendencies" is delicate, one must do it properly weighted with the frequency of occurrence $\rho_\mu(y)$ to achieve an answer independent of initial state but characteristic of the model.

There is a rather good monograph called *Atmospheric Data Analysis* by R. Daley published in 1991, before much of the recent work on data assimilation stimulated by Courtier and Talagrand which resulted in changes in the ECMWF operational system circa 1996. In this monograph Daley discusses an idea attributed to Charney, Halem and Jastrow from 1969 on using observations to determine an accurate state of a climate/weather system. The idea is that one measures a subset $z(n)$ of the total set of climate variables $x(n)$, and uses these in the dynamical equations to drive the solution of the dynamical equations to a state of the climate/weather system. If one has as dynamical variables $x(n) = (u(n), z(n))$, then the idea is to take the observed $z(n)$ variables $z_0(n)$ and use them as an external driving for the equations of motion

$$\begin{aligned} u(n+1) &= A(u(n), z(n), \mu) \\ z(n+1) &= B(u(n), z(n), \mu) + K(z_0(n) + (n) - z(n)) \end{aligned}$$

and for large enough $K$ one hopes that the external driving from the observations will cause

$$\begin{aligned} u(n) &\rightarrow u_{\text{unobserved but accurate}}(n) \\ z(n) &\rightarrow z_0(n) \end{aligned}$$

In contemporary studies of nonlinear systems this is known as synchronization of the state $x(n) = (u(n), z(n))$ to the state of the observed system using only a subset of the observed variables for the synchronization. In general it

cannot happen *unless* the autonomous driven system

$$\begin{aligned} u(n+1) &= A(u(n), z(n), \mu) \\ z(n+1) &= B(u(n), z(n), \mu) \end{aligned}$$

is *exactly* the same as the driving system for only under those circumstances can $z(n) = z_0(n)$ be a solution of the dynamical equations. This is surely not the case in climate modeling, so the synchronization which is sought cannot occur. What might occur is that with $K$ large enough, the variation of $z(n)$ will approach the observations and the rest of the dynamical variables will go to another evolution which has little to do with the actual state of the ocean/atmosphere system.

# B APPENDIX: CSM Models

## B.1 Cloud System Models (CSMs) or Cloud Resolving Convection Parametrization (CRCP) and ARM

Dave Randall in his briefings to JASON on the ARM program described a method for improving the "parametrizations" of GCMs by introducing a two dimensional "cloud model" within each grid box of a GCM. This 2D model is aimed at resolving, without a full blown 3D computation, the dynamics of some smaller scale processes occurring sub-grid scale on the GCM or large scale dynamics. Standard practice assumes GCM grid wide parameters to represent these smaller scale processes while the CSM (or CRCP) models compute the smaller scale processes "on the fly".

In another section of this report we argue that this approach requires order 100 times more computing than present GCM modeling based on present GCM resolution.

The formulation of these CSM models has been based largely on the work of W. W. Grabowski. The idea is to split the overall dynamical variables including wind $V(x, y, z, t)$, temperature $T(x, y, z, t)$, etc. into a large scale part depending on $(x, y, z, t)$ and a small scale part depending only on ($x$-east-west, $z$—vertical, $t$). The y-north-south dependence is eliminated in the small scale process under the physical assumption that the general trend of the wind to advect from west to east would be an important aspect of small scale dynamics (but not over the oceans!).

In any case the wind field is written as $V(x, y, z, t) = U(x, y, z, t) + u(x, z, t)$, and the other variables are decomposed in a similar fashion. Then

equations are written for each of the large scale fields, such as $U(x, y, z, t)$, and the small scale fields, such as $u(x, z, t)$. The large scale fields are taken to satisfy

$$\left(\frac{\partial}{\partial t} + U(x, y, z, t) \cdot \nabla\right) U(x, y, x, t) = \nabla P(x, y, z, t) - f \times U$$
$$+\hat{z}gB + \hat{x}F_{small} + \nu\nabla^2 U(x, y, z, t)$$

where the gradient is $\nabla = (\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z})$, and the small scale fields $u(x, z, t)$ satisfy

$$\left(\frac{\partial}{\partial t} + u(x, y, z, t) \cdot \nabla'\right) u(x, y, z, t) = -\nabla p(x, z, t) + \hat{z}gb + \hat{x}f + \nu\nabla'^2 u(x, z, t)$$

and $\nabla' = (\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial x})$, along with equations for the pressures $P, p$, the buoyancies $B, b$, and for the thermodynamical variables such as potential temperature which enter the buoyancies. The final term in each equation is dissipation while $f_{large}(x, z, t)$ and $f_{small}(x, y, z, t)$ represent the effect of the large scales on the small scale, $u(x, z, t)$, dynamics and of the small scales on the $U(x, y, z, t)$ dynamics.

The forcing functions are chosen to be

$$f_{small} = \frac{U_x(x, t, z, t) - \langle u \rangle(x, t, z, t)}{\tau_m}$$

while $f = -f_{small} \cdot \tau_m$ is "the time scale of the kinematic coupling." The issue of which combination of these forcings depends on which independent variables is left somewhat to our imagination.

The choice of forcing appears rather *ad hoc* given that one could choose the connections between large and small scale motions in another way, directly from the primitive equations for $V(x, t, z, t)$ .

The equations for the overall velocity field satisfies

$$\left(\frac{\partial}{\partial t} + V(x, y, z, t) \cdot \nabla\right) V(x, y, z, t) = -\nabla(P(x, y, z, t) + p(x, z, t)$$
$$-f \times V(x, +\hat{z}g(B + b) + \nu\nabla^2 V(x, y, z, t)$$

where the dissipation could be biharmonic, but still linear in $V(x,y,z,t)$.

If we take the decomposition $V(x,y,z,t) = U(x,y,z,t) + u(x,z,t)$ seriously then the equations for $V(x,y,z,t)$, can be easily decomposed into an equation for $U(x,y,z,t)$ and an equation for $u(x,z,t)$:

$$\left(\frac{\partial}{\partial t} + U(x,y,z,t)\cdot\nabla\right)U(x,y,z,t) = -\nabla P(x,y,z,t) - f\times U(x,y,z,t) +$$
$$\hat{z}gB - u(x,z,t)\cdot\nabla' U(x,y,z,t) + \nu\nabla^2 U(x,y,z,t)$$

and an equation for $u(x,z,t)$:

$$\left(\frac{\partial}{\partial t} + u(x,z,t)\cdot\nabla'\right)u(x,z,t) = -\nabla p(x,z,t) + \hat{z}gb - f\times u(x,y,z,t)$$
$$-u(x,y,z,t)\cdot\nabla' u(x,z,t) + \nu\nabla'^2 u(x,z,t)$$

This identifies the forcing from small scales to large scales as $-u(x,z,t)\cdot\nabla' U(x,y,z,t)$ and the forcing from large scales to small scales as $-U(x,y,z,t)\cdot\nabla' u(x,z,t)$, both of which are natural as the advection of the large scale velocity field $U(x,y,z,t)$ due to the small scale field and vice versa. The only question which needs answering is what to do with the dependence on $y$ in the forcing of the $u(x,z,t)$ equation by $-U(x,y,z,t)\cdot\nabla' u(x,z,t)$. A simple prescription is to integrate this equation over the domain in $y$ thus averaging over the direction "perpendicular to the mean wind" which is in accord with the original decomposition anyway. The Coriolis forces $-f\times u(x,z,t)$ in the small scale equation may be neglected because of the small scales, a few km, on which they are to operate.

Finally, the use of the two dimensional small scale CSM dependent on $(x,z,t)$ could be altered to account for the "mean large scale wind" determined by $U(x,y,z,t) = (U_x(x,y,z,t), U_y(x,y,z,t), U_z(x,y,z,t))$. Since the vertical wind is typically much smaller than the horizontal components using the usual shallow water arguments, one might take for the small scale CSM

velocities $u(x\cos(\theta) + y\sin(\theta), z, t)$ where $\theta$ is where is

$$\tan(\theta) = \frac{|U_y|}{|U_x|}$$

for the large scale wind at each (previous) time step and in each large scale grid box. This would involve some additional calculation but align the small scale dynamics along the immediate, nearly east-west, wind direction.

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